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TH-3 Microwave Radio System:

Networks

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This paper describes the filters and networks which provide the frequency selectivity required in the TH-3 microwave transmitter and receiver, and the equalizers, which compensate amplitude and delay distortions introduced by the filters.

I. INTRODUCTION

The frequency selectivity required by the microwave transmitter and receiver of the TH-3 radio system is provided by passive networks. Adjacent-channel selectivity, together with suppression of second and third harmonics of the intermediate frequency (IF) which are generated in the receiving modulator and IF preamplifier, is provided by a loss- and delay-equalized intermediate-frequency filter. Microwave filters and selective networks provide image-frequency and adjoining-channel selectivity, furnish the required discrimination against unwanted tones and noise originating in the microwave generator, and are used for the multiplexing of transmitters and receivers into a common antenna-feed waveguide. Microwave delay equalizers compensate for the envelope delay distortion (EDD) of the selective microwave transmission networks,* so that only a relatively small residue of EDD remains to be mopped up by IF delay equalizers.

II. MICROWAVE TRANSMISSION NETWORKS

The locations and functions of the selective microwave transmission networks are described in another paper in this issue,[1] where overall requirements for the transmitter and receiver selectivities are also pre-

* We define transmission networks and transmission paths as those which carry the modulated signal.

sented. The transmission path of the transmitter contains two such networks, the transmitter microwave network, which precedes the traveling-wave tube (TWT), and the channel combining filter, which follows the TWT and serves the dual functions of multiplexing four transmitters into a common antenna feed waveguide and of providing a substantial part of the required transmitter RF selectivity. The channel separation network serves as the receiver multiplexer and also provides all receiver RF selectivity. The receiver microwave filter adds the receiver microwave carrier (RMC) to the received signal for application to the receiver modulator. It furnishes selectivity in the RMC path, for noise reduction, but none in the transmission path. To minimize transmission and delay irregularities due to reflections, all microwave networks are required to present return losses in excess of 30 dB at all frequencies which must be transmitted.

2.1 *Transmitter Microwave Network*

The transmitter microwave network consists of a bandpass filter, fabricated in WR-159 waveguide, and a one-section microwave delay equalizer of the type developed by T. A. Abele and H. C. Wang.[2]

The electrical requirements for this network evolved from four considerations. These are:

(*i*) This network must provide enough attenuation of the transmitter modulator's carrier leak, at a frequency $f_0 - 70$ MHz,* and unused lower sideband, at $f_0 - 140$ MHz, to prevent overload of the TWT and interference with measurements of the desired sideband.

(*ii*) This network and the channel combining filter, together, must fulfill the overall transmitter RF selectivity requirements.

(*iii*) The EDD of the transmitter microwave network must be less than 0.2 ns over the range $f_0 \pm 9$ MHz. (The importance of minimizing EDD, in this network especially, has been emphasized in another paper in this issue.[1])

(*iv*) The combined selectivity, and therefore the EDD, of the remaining microwave networks of the hop (i. e., channel combining and separating networks) must be such that the EDD can be compensated by a single microwave delay equalizer.

Conflicting implications of these considerations led to equal division of the transmitter out-of-band RF selectivity requirements between the transmitter microwave network and the channel combining filter,

* f_0 is the center frequency of the network's passband.

with resulting requirements for the transmitter microwave network as follows:

Envelope Delay Distortion,	(f_0 to $f_0 \pm 8.5$ MHz)	$\leqq 0.2$ ns
Envelope Delay Distortion,	(f_0 to $f_0 \pm 15$ MHz)	$\leqq 1.0$ ns
Insertion loss, in-band	(f_0 to $f_0 \pm 15$ MHz)	unspecified*
Insertion loss, $f_0 - 70$ MHz		$\geqq 49.5$ dB
Insertion loss, $f_0 - 140$ MHz		$\geqq 50.5$ dB

The filter of this network is realized as a six-resonator quarter-wave-coupled bandpass structure, based on a lossless maximally-flat-amplitude prototype having a 3-dB bandwidth of 54.2 MHz. Each resonator is bounded by inductive obstacles in the form of arrays of three cylindrical posts. To compensate for the asymmetry of the delay characteristic which results from ohmic losses slight adjustments were made in the lengths of the coupling lines. Figure 1a shows a view of this network and Fig. 1b a sectional view of the delay equalizer. Typical performance characteristics appear in Fig. 2.

2.2 *Channel Combining Filter and Channel Separating Network*

Examples of the channel combining filters and channel separating networks which serve as RF multiplexers for the radio transmitters and receivers, respectively, are shown in Fig. 3. Although the combining filter and separating network differ in details of structure and electrical requirements, similarities in their design principles and physical configurations, together with the facts that they share a common microwave delay equalizer and, to a large extent, complement each other with respect to electrical requirements, make it convenient to describe them together.

The directional filter configuration developed by Abele,[3] consisting of series-connected microwave bandpass and band-rejection filters of equal order, formed the starting point in the design of these multiplexers. The directional filter has the following advantages over the constant-resistance networks[4] used for multiplexing in earlier Bell System microwave equipment:

(*i*) Only two components, a bandpass filter and a band-rejection filter, are required to provide all needed receiver RF selectivity instead of the five (two hybrid junction, two band-rejection filters, and one

* The insertion loss of delay-equalized microwave filters is characteristically very uniform throughout the equalized portion of the passband—of the order of a few hundredths of a decibel for the subject filters. IF mop-up loss equalization compensates these small residual shapes.

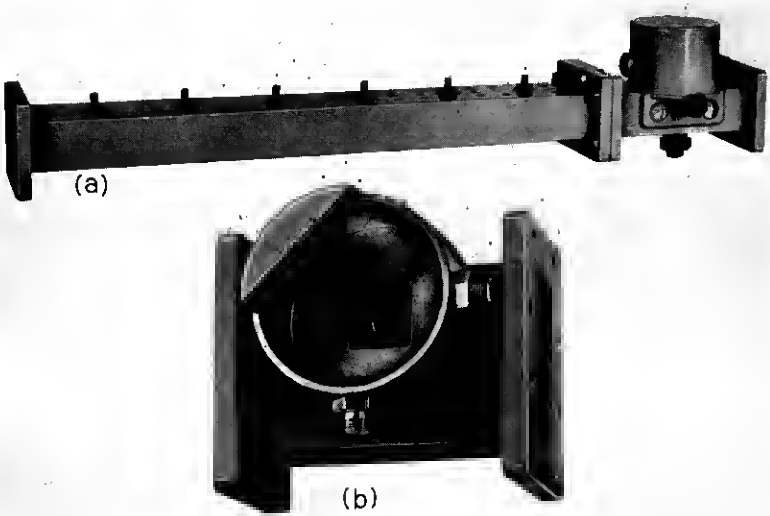

Fig. 1—Transmitter microwave network: (a) complete network; (b) sectional of delay equalizer.

bandpass filter) in the corresponding assembly in constant-resistance form.

(*ii*) The symmetric "T" shape of the directional filter facilitates design of equipment for either "right-handed" or "left-handed" installation.

Abele's directional filter[3] is derived from a true complementary pair, i.e., bandpass and bandstop sections of equal order, necessary if the common-port reflection coefficient of the prototype is to be zero at all frequencies. To conserve space, effect economies in manufacture, and reduce adjacent-channel delay distortion in the "through" paths to physically adjoining bays via the band-rejection section, pseudo-complementary designs were evolved for these filters by programming a digital computer to present the significant transmission and reflection parameters of a complementary prototype, then arbitrarily removing resonators from the band-rejection section, and readjusting the loaded Q's of the remaining ones for optimum performance in terms of system requirements. After satisfactory prototypes were obtained, the microwave elements were synthesized, using essentially the method of W. W. Mumford[5] for the bandpass section and that of Wang[6] for the band-rejection section. The latter entails application of transmission-

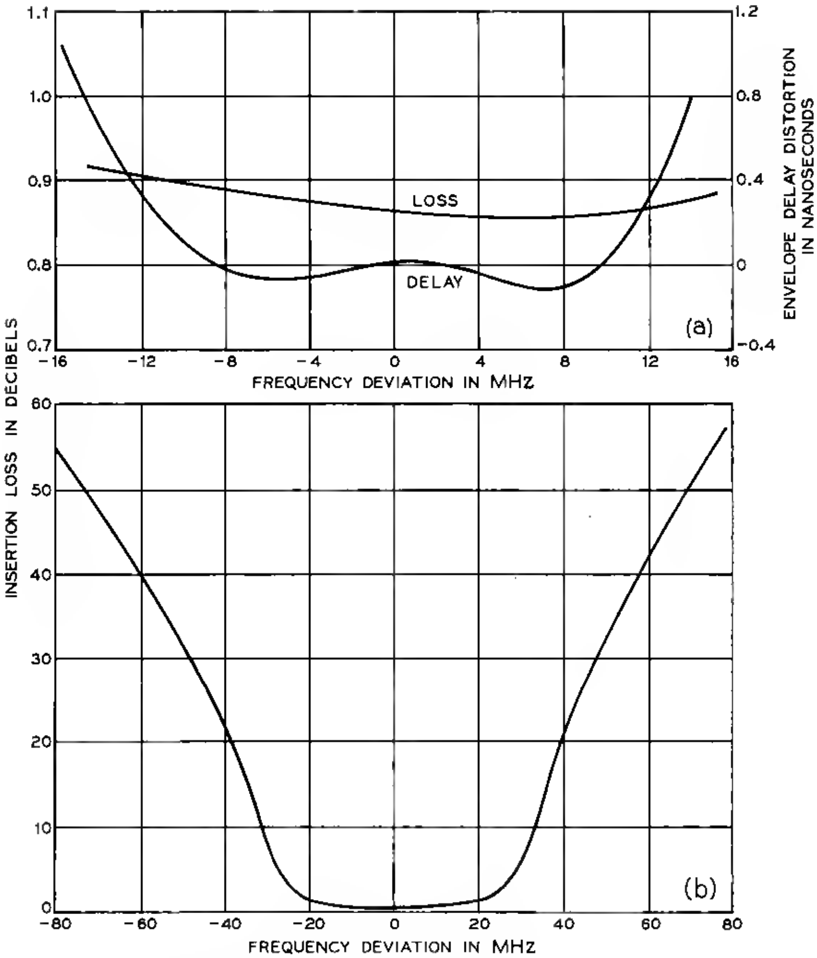

Fig. 2—Typical characteristics of transmitter microwave network: (a) passband EDD and insertion loss; (b) stopband insertion loss.

line synthesis methods and results in a design which has excellent symmetry, required for a satisfactory "fit" with the companion bandpass section, and passband return loss, but requires variations in the characteristic impedances of the coupling lines between resonators. This is achieved by replacing part of the broad wall of the waveguide with a "stepped" plate.

Out-of-band selectivity requirements for the bandpass path of the channel combining network are identical to those of the transmitter

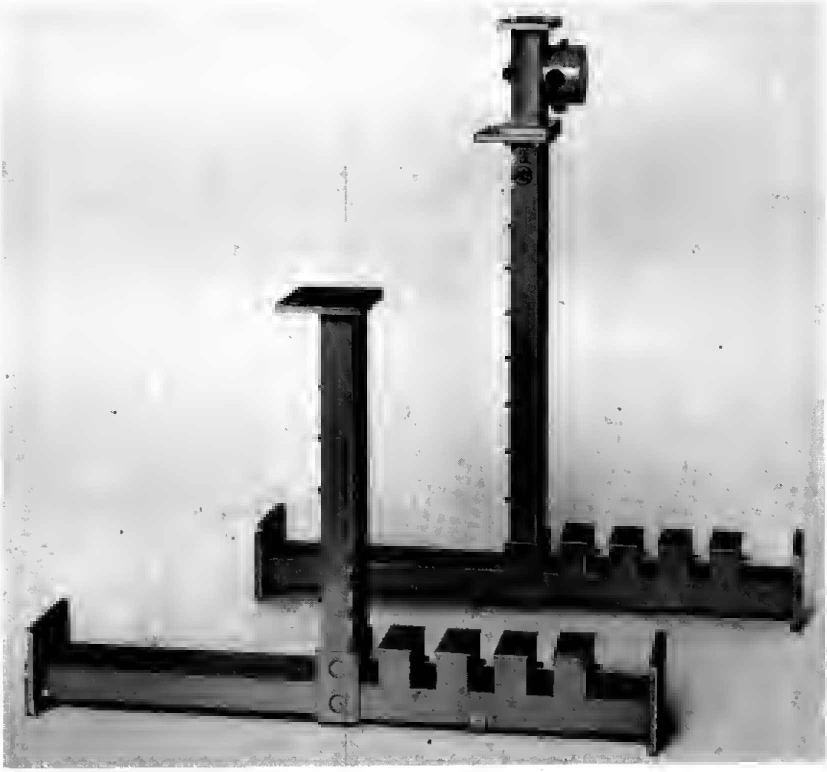

Fig. 3—Channel combining filter (left) and separating network (right).

microwave network as given in Section 2.1. In-band requirements are associated with those of the corresponding channel separating network, and will be covered in a later paragraph.

The microwave realization of the bandpass section of the channel combining network consists of a singly terminated, maximally flat, six-resonator, quarter-wave-coupled assembly, based on a lossless prototype having a 3-dB bandwidth of 54.15 MHz. The section is fabricated in WR-159 waveguide, with resonators bounded by inductive obstacles in the form of transverse arrays of cylindrical posts. The band-rejection section is also fabricated of WR-159 waveguide, and contains four resonators, with parameters determined as described in the preceding paragraph.

The out-of-band selectivity requirements for the bandpass path of the channel separating network are obtained by subtracting from the overall requirements (see Table I of the second paper in this issue)

the sum of (*i*) the insertion loss of the transmitter microwave network, and (*ii*) the insertion loss of the channel combining network at each significant frequency. The governing requirement turns out to be that discrimination of 9 dB is required at a frequency $f_0 \pm 29.7$ MHz.

As in the case of the transmitter microwave network, in-band requirements for the channel combining filter and channel separating network were established on the basis of EDD, with the specific criterion that the EDD of the transmission path between the combining port of a channel combining network and the separating port of the companion separating network be less than 0.4 ns over the frequency range $f_0 \pm 9.0$ MHz, and less than 4.0 ns over the range $f_0 \pm 15$ MHz. With the design, and therefore the EDD, of the channel combining network established, there remained to be determined the order and bandwidth of a bandpass section for the channel separating network which would provide the required out-of-band selectivity, and also, together with the companion combining network, have EDD within the range which could be accommodated by a technically and economically feasible microwave equalizer. An eight-resonator, singly terminated, maximally-flat-amplitude section having a 3-dB bandwidth of 51.8 MHz was found to have the requisite properties, and the separation network is based on this. With the exception of the two additional bandpass resonators, the directional filter of the separation network is similar to that of the combining filter. The delay equalizer is much like the one used on the transmitter microwave filter, and is attached as shown in Fig 3. Insertion loss characteristics of a combining network and a separating network are shown in Figs. 4a and b, respectively, and their combined EDD in Fig. 4c.

2.3 *Receiver Microwave Filter*

The receiver microwave filter combines the signal with the receiver microwave carrier for application to the Schottky-barrier receiving modulator, and also provides selectivity in the RMC path to suppress noise. This is a true complementary directional filter, with three-resonator bandpass and band-rejection sections. Its design is based on a maximally flat, lossless prototype having a 3-dB bandwidth of 4.94 MHz. Since this filter is not required to accommodate large bandwidths in the pass regions of its band-rejection section, the stepped-impedance connecting lines were omitted, with resulting savings in cost. Electrical requirements are:

Insertion loss at f_0, RMC port to modulator port $\leqq$ 3.8 dB
Insertion loss at $f_0 \pm 70$ MHz, RMC port to modulator port $\geqq$ 44.5 dB

Attenuation slope, signal port to modulator port, $f_0 + 60$ MHz to $f_0 + 80$ MHz, $\leqq 0.65$ dB
(f_0 = RMC frequency)

2.4 *Microwave Generator Tone Suppression Filter*

At the output of the microwave generator, spurious tones were detected and found to be harmful in some cases, since they appeared in the baseband signal frequency. The 5/6, 11/12, 13/12, and 7/6th harmonics of the transmitter modulator carrier frequency are present and can cause unwanted baseband tones. A two-cavity bandpass filter is added at the output of the microwave generator to suppress these tones. Because the output of the generator is in WR-112 waveguide, this size was also chosen for the filter. Because of the narrow separation between the operating frequency and the cutoff frequency of WR-112 guide, special considerations were given to these filters to reduce the passband insertion loss and to avoid possible "holes" in the stop band. It was concluded that for best electrical performance, filters for the low-frequency channels must use capacitive obstacles and filters for high-frequency channels must use inductive obstacles. For cost considerations, there are only four mechanical codes and each code may be tuned electrically to eight different channels (including staggered frequency channels). The three codes for low-frequency channels are designed in the form of two-cavity, maximally flat, direct-coupled bandpass filters with capacitive windows, while the fourth code, for high-frequency channels, has the form of a two-cavity, maximally flat, quarter-wavelength-coupled bandpass filter with inductive posts.

III. IF NETWORKS

3.1 *Function*

The IF networks that are required in the long-haul application of the TH-3 microwave radio system are shown in Fig. 5.

The bandpass filter provides adequate suppression to the adjacent channels which are received along with the desired signal. The bandpass filter also provides attenuation to the second and third harmonics generated in the preamplifier so that echo-like intermodulation noise is sufficiently reduced.

The delay and amplitude equalizers compensate for the delay distortions caused by the band-elimination portion of the directional

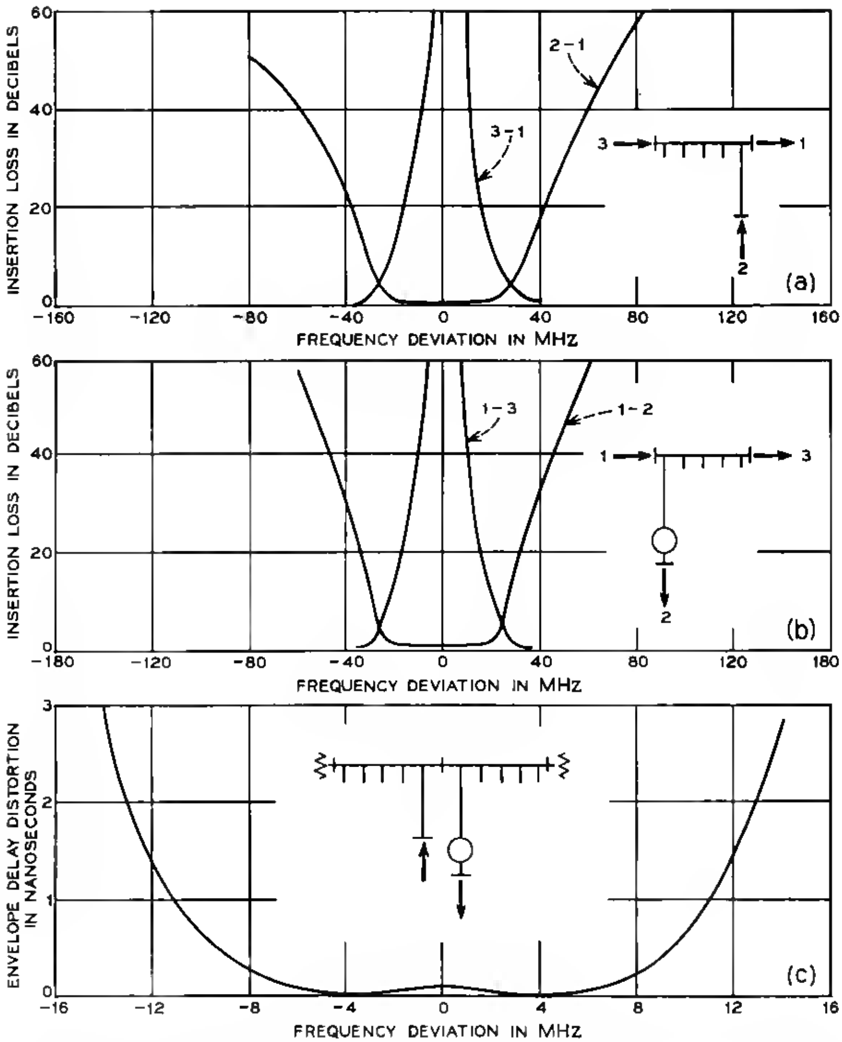

Fig. 4—Typical characteristics of channel combining filter and separating network: (a) insertion losses, combining filter; (b) insertion losses, separating network; (c) EDD, combining filter and separating network together.

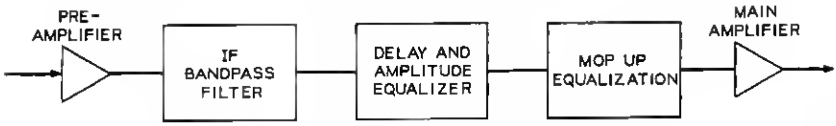

Fig. 5—Location of IF transmission networks in the TH-3 microwave radio system.

filters in the adjacent channels, and for the small residual in-band amplitude distortion of the microwave networks.

The "mop-up" equalizers correct for delay slope that arises due to normal systems variations. This correction is necessary because the intermodulation noise of the radio system is very sensitive to delay slope.

3.2 *IF Bandpass Filter*

Most circuits in the TH-3 repeater that contain active devices are relatively broadband and therefore introduce little transmission distortion. The IF bandpass filter in-band characteristic could be the controlling factor in the intermodulation noise performance of the repeater. Therefore the IF bandpass filter is both delay and amplitude equalized.

3.2.1 *Design Objectives*

The delay and amplitude distortion allowed in the passband is specified as the amount of intermodulation noise, caused by the in-band distortions, contributed by the filter. The transmission requirements for this filter are based on its contributing 0 dBrnc0 or less intermodulation noise per filter. This would be equivalent to a 30-dBrnc0 noise contribution in a 4000-mile system. The calculation of noise is based on an 18.6 log N law of addition, which was found in laboratory measurements on a system containing a similar filter.

Intermodulation noise contributed to the system by the filter is caused by transmission deviations and echoes.

The transmission deviations are the residual delay and amplitude ripples of the filter after it has been equalized. The delay and amplitude tolerances of the filter are based on the worst case peak-to-peak ripple and period of ripple that could occur in the equalized filter. The in-band objectives, based on noise performance, and the out-of-band objectives, based on adjacent channel interference and harmonic rejection, are as follows:

Frequency (MHz)	Delay (ns)	Discrimination (dB) Relative to 70 MHz
66–74	±0.15	
57.5–82.5	±0.25	
60–80		±0.03
56–84		±0.05
39.35–41.35		>20
98.65–100.65		>20
130–150		>25
200–220		>25

In addition, an insertion loss of 4.0 ± 0.2 dB at 70 MHz has been alloted to the filter.

The amplitude shape of the filter passband between 56 and 84 MHz should not have any parabolic component in its characteristic. A parabolic component in the amplitude characteristic would not add to the intermodulation noise, but would cause baseband rolloff.

Impedance mismatches between the filter and the apparatus interfacing the filter can generate echoes. One condition for the generation of an echo is a transmission path over which a fraction of the original signal is reflected and delayed in time from the original signal. Delay and amplitude distortions result from this reflected signal.

In order for the impedance mismatches not to contribute significantly to the intermodulation noise, the level of the echo or reflected signal should be well below the original signal. The measure of impedance mismatch used in this discussion is return loss in dB. To meet the desired echo level, the sum of the return losses at the filter interfaces should be at least 60 dB.

With reference to Fig. 5, the output return loss of the preamplifier is ≧35 dB and the input return loss of the delay and amplitude equalizers is ≧30 dB. In order to meet the 60-dB requirement the input return loss of the filter must be ≧25 dB, and the output return loss ≧30 dB.

3.2.2 *Theoretical Design*

Both the image parameter and insertion loss design of the filter were explored. The insertion loss method[7,8] is a more exact method in that either the passband insertion loss ripple, or the return loss ripple can be specified. Then a circuit configuration realizing these characteristics is synthesized. The design of this filter must be a compromise between the in-band return loss and the delay distortion at the passband edges.

The delay distortion must be kept to a minimum since approximately one-half of the entire configuration consists of delay equalization.

An 8th-order filter was synthesized[9] which has one attenuation pole at zero and one at infinite frequency, and three finite attenuation poles, one below and two above the passband. This filter, shown in Fig. 6a, was synthesized with an equal passband ripple of 0.01 dB, which is equivalent to a return loss of 26.4 dB. It has unequal terminations, i.e., an input impedance of 75 ohms and an output impedance of 66 ohms. Norton and pi-delta transformations were made on this configuration to achieve equal terminations and to get a capacitor to ground from every node of the filter and a capacitor across each inductor. The additional capacitors in the transformed filter, shown in Fig. 6b, are used to compensate for parasitic capacitance.

The input return loss of 26 dB meets the filter requirements; however, the output return loss of 26 dB is 4 dB below the required 30 dB. In order to increase the output return loss, a 2-dB bridged-T loss pad is connected in tandem with the output of the filter. The output return loss is now increased by twice the loss of the pad (4 dB) to the re-

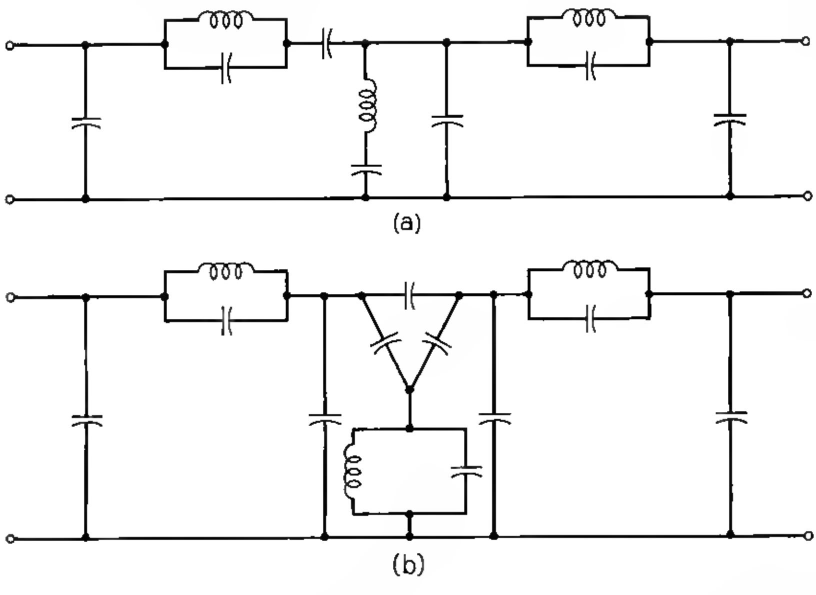

Fig. 6—(a) Schematic of the computed configuration for the filter section of the 1044A filter. (b) Schematic of the transformed configuration for the filter section of the 1044A filter.

quired 30 dB. The pad will also serve as a buffer between the filter section and the delay and loss equalization.

Three bridged-T all-pass sections are used to equalize the delay distortions of the filter to within the design objectives. Since there is a finite Q associated with the elements used in the filter and delay equalizer section, their loss shapes tend to be complementary thus leaving only a positive loss shape to be equalized. The loss equalizer is a bridged-T capacitor section which has an insertion loss with a negative slope. This equalizer is combined with the loss pad to form a single loss section.

Bridged-T configurations are used in order to achieve high return losses.

The complete schematic for the 1044A filter is shown in Fig. 7.

3.2.3 *Measured Performance and Mechanical Assembly*

A typical measured characteristic along with the manufacturing requirements for the 1044A filter are shown in Figs. 8 and 9. The return losses (compared to 75 ohms) meet the requirements previously specified.

Field tests showed that the noise contributed by the filter to the system is less than 0 dBrnc0. These tests also indicate that the baseband rolloff due to the filter meets system requirements.

The 1044A filter is assembled on a printed wiring board and housed in a drawn steel can (see Fig. 10). Sections of the filter are shielded by the use of aluminum cans which are mounted to the printed wiring board.

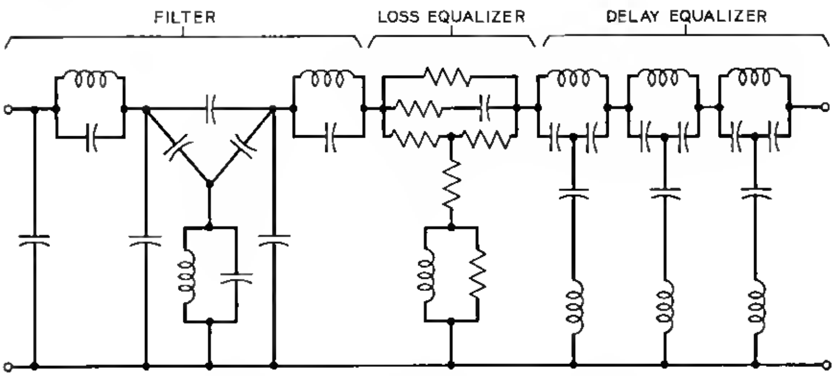

Fig. 7—Schematic diagram of the 1044A filter.

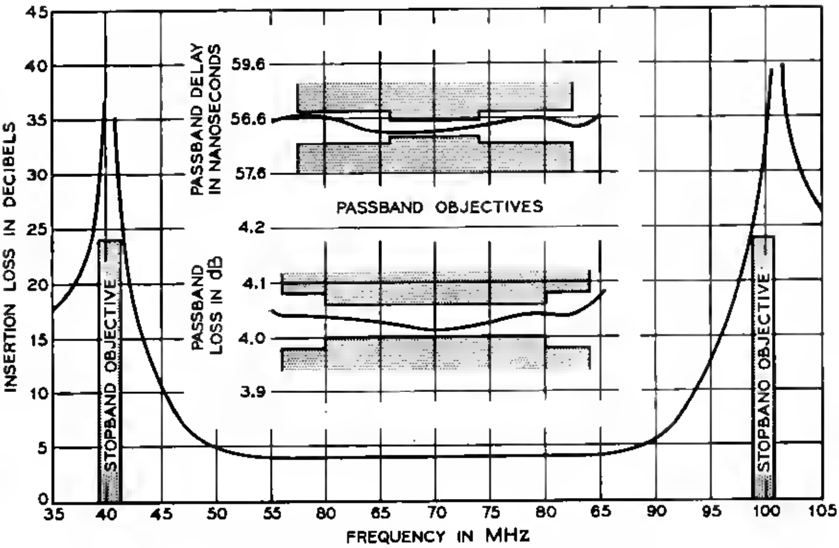

Fig. 8—Passband characteristic of the 1044A filter.

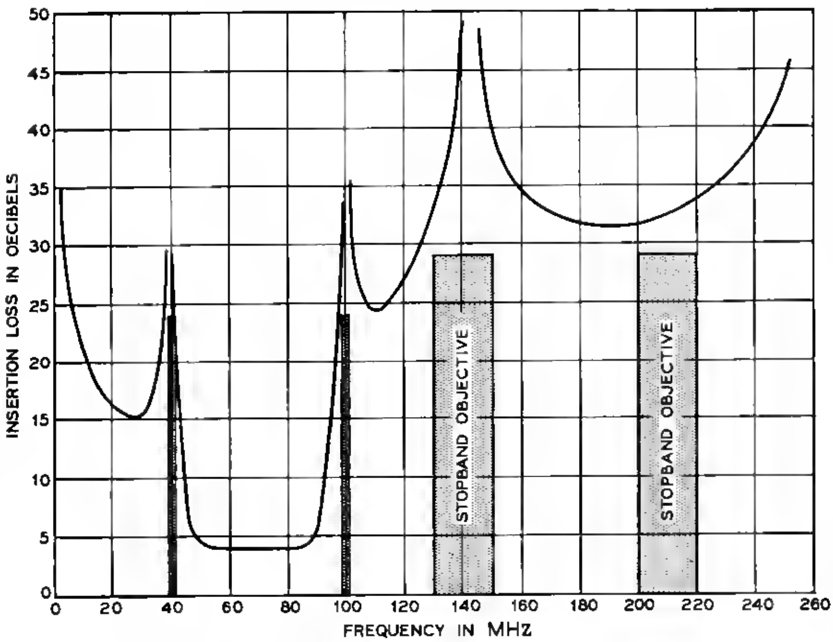

Fig. 9—Stopband characteristic of the 1044A filter.

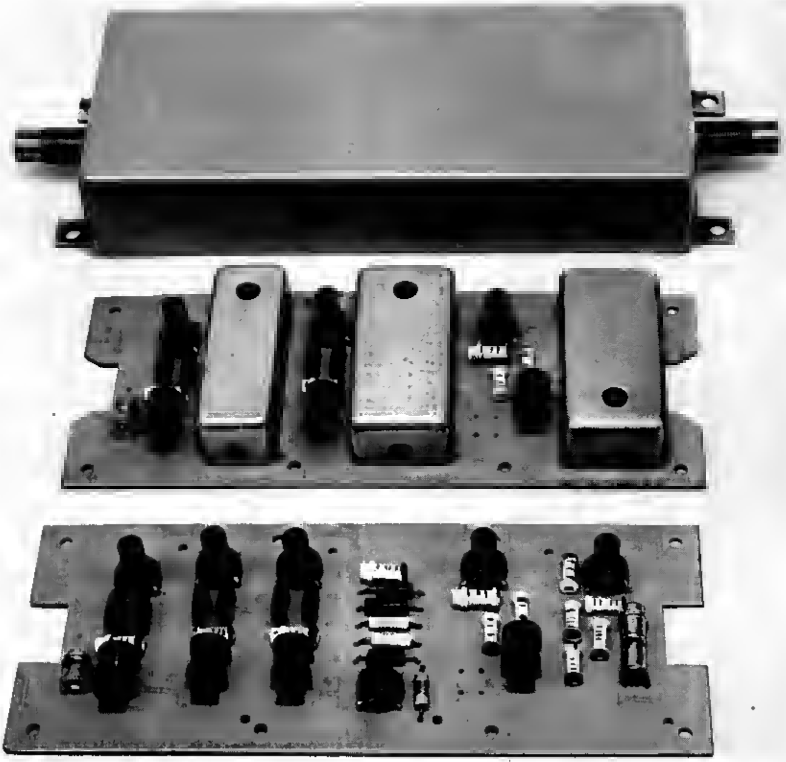

Fig. 10—The 1044A filter.

3.3 *Delay and Amplitude Equalization*

3.3.1 *General*

The microwave channel combining filters and channel separating filters have been designed as directional filters as described earlier in this paper. The bandpass portion of these filters produces a delay distortion in the passband which is equalized at microwave frequencies. The band-elimination portion of these filters produces a delay distortion at the frequencies of the adjacent channels. The shape of the delay distortion caused by this effect depends upon the bay lineup. That is, if a given channel passes only through the directional filter of the adjacent channel at a lower frequency, then only the distortions caused by that directional filter needs to be corrected for. If the signal passes through no adjacent channel filters then no delay correction is

required; however, an amplitude equalizer would be required to compensate for the small residual in-band amplitude shape. Consequently, three different IF delay and amplitude equalizers are necessary to correct for the three possible delay shapes caused by adjacent channel directional filters. A fourth equalizer is needed to correct for amplitude shape only. All four of the equalizers provide the same amplitude shape.

3.3.2 *Requirements*

The three delay shapes are basically a positive slope, a negative slope, and parabolic. The requirements for these equalizers are shown in Fig. 11.

The electrical design for the delay and amplitude section for these networks is of the same type as those used in the 1044A filter.

All requirements that were specified on these networks were met and are as follows:

Frequency (MHz)	Delay Match (ns)	Loss Match (dB)	Return Loss (dB)
55–85	±1.0	±0.10	30 min
58–82	±0.4	±0.05	30 min
61–79	±0.3	±0.03	33 min
70	—	2.2±0.1	—

3.4 *"Mop up" Equalization*

The "mop up" equalization used in the TH-3 radio system is the same as that used in the TD-3 radio system. These equalizers are completely described in Ref. 10 and are only mentioned here for completeness.

IV. ACKNOWLEDGMENTS

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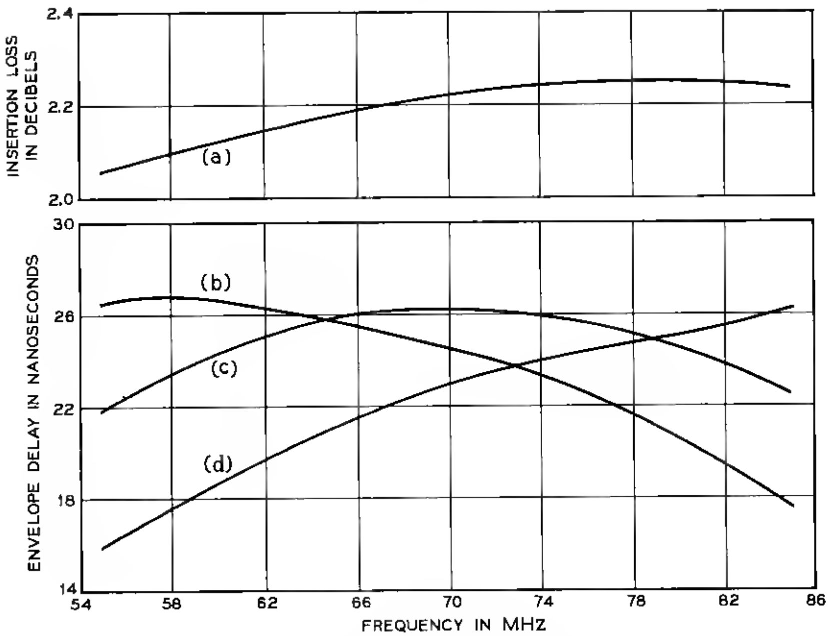

Fig. 11—(a) Insertion loss of the 936A, B, C, and D equalizers and envelope delay of the (b) 936B, (c) 936C, and (d) 936D equalizers.

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